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Experimental overview on flow observables in heavy ion collisions

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Abstract

This paper summarizes the experimental results on flow phenomena that were presented at Quark matter 2015, with a focus on new flow observables and correlations in small systems. The results presented include event-shape selected p_{T} spectra and v_n measurements, correlations between flow harmonics of different orders, study of factorization breakdown in two-particle correlations, and principal component analysis of two-particle correlations. Recent developments in investigation of collective effects in small collisions systems, namely, p+A, d+A and ^{3}He + A as well as in pp collisions are also presented.

Keywords: Heavy Ion Collisions, Quark Gluon Plasma (QGP), Harmonic Flow

1. Introduction

Flow measurements have lead to an understanding of the initial geometry, such as the initial energy density profiles, as well as the dynamical properties, such as the viscosity to entropy density ratio (η/s), of the medium produced in heavy ion collisions. However, sensitivity to both initial geometry and η/s acts as a double edged sword, and it is difficult to tightly constrain either of these using the traditional v_n measurements. To address this issue, several new flow observables have been recently developed, which are sensitive to one but not the other. The first measurements of these observables are discussed in this paper.

A quantum leap in the understanding of heavy ion collision took place a few years back with the realization that there are large event by event fluctuations in the collision geometry. Similarly, it is now realized that the event-plane angles Ψ_n which were previously assumed to be constant for a given event, have explicit dependence on p_{T} and pseudorapidity η. The first observables that measure these longitudinal and p_{T} dependent Ψ_n fluctuations are presented.

Recently, the measurement of flow like correlations in p+A collisions have resulted in intense debate on whether these effects are indeed collective in origin, or arise from initial geometry effects. Identifying the origin of these correlations, as well as determining how small a system size one can go to where such correlations are present, have been some of the most important questions in flow measurements. This has now been further investigated by several measurements of inclusive as well as identified charged hadron v_n measurements in pp, p+A, d+A and ^{3}He + A collisions, which are discussed in this paper.

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2. Measurements

2.1. Event-shape selected v_n measurements

Measurements of event-by-event v_n distributions in heavy ion collisions have shown that even within a narrow centrality class, there is considerable variation in the initial geometry, due to fluctuations in the positions of the colliding nuclei [1]. These fluctuations lead to variations in the v_n within a typical 5% wide centrality class, that are comparable to the variation in the mean v_n across all centralities. Traditionally for flow measurements, the centrality has been used as a proxy for event-geometry, which leads to intermixing of event-shape dependent effects with event-size dependent effects. Recently it was proposed to perform measurements, when selecting both on the centrality as well as the geometry of a given event [2]. Such "Event-shape selected" v_n measurements reveal several hidden correlations between the flow harmonics and improve our understanding of the hydrodynamic response to the initial geometry . Detailed event-shape selected flow measurements were recently performed in Pb+Pb collisions at $\sqrt{s_{\rm NN}}$=2.76 TeV by the ATLAS [3] and ALICE collaborations [4]. In the ATLAS measurements, the selection on the geometry of the event was done by measuring the integrated v_n (called q_n) in the ATLAS Forward calorimeter (3.2< $|\eta|$ <4.9), and categorizing the events into classes of event-ellipticity or triangularity based on the q_2 and q_3 respectively. The v_n were measured using the ATLAS inner detector covering $|\eta|$ <2.5, thus ensuring that the same set of particles are not used to select on the event-shape and to perform the v_n measurements. In the ALICE measurements, a similar strategy was employed.

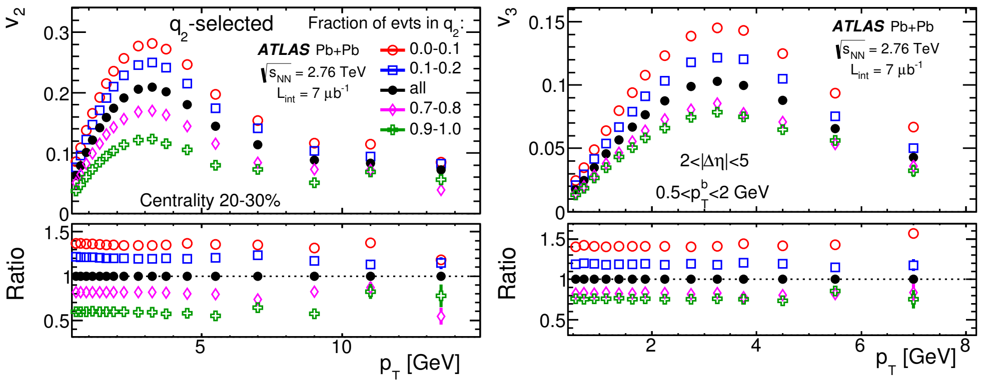

Fig. 1. The v_2 (left panel) and v_3 (right panel) as a function of $p_{\rm T}$ in the (20-30)% centrality interval. The different graphs correspond to different q_2 (left panel) and q_3 (right panel) classes. The q_n ∈(0.0-0.1) corresponds to the 10% of the events with the largest q_n, while the q_n ∈(0.9-1.0) corresponds to the 10% of the events with the smallest q_n. The solid black points correspond to the inclusive case (*i.e.* when not binning in q_n). The lower sub-panels shows the ratio of the different q_2 (q_3) to the inclusive v_2 (v_3). Figure taken from [3].

Figure 1 shows the $v_2(p_{\rm T})$ (left panel) and $v_3(p_{\rm T})$ (right panel) when selecting on different q_2 and q_3 classes respectively, within the (20–30)% centrality interval. It is seen, perhaps trivially, that selecting events with a larger $q_2(q_3)$ leads to events with larger $v_2(v_3)$. This simply implies that events with larger v_n at forward rapidity have larger v_n at mid-rapidity. The interesting observation is actually seen in the lower panels which show the ratio of the q_n selected v_n to the inclusive v_n for the (20–30)% centrality class. This ratio is almost independent of $p_{\rm T}$ up to ~10 GeV for v_2 and up to ~5 GeV for v_3. This shows that for a fixed centrality (or system-size) when one picks events with different collision geometries, the increase or decrease in the v_n is independent of the $p_{\rm T}$. This implies that the hydrodynamic response in heavy ion collisions factorizes into an initial geometry dependent part and a $p_{\rm T}$ dependent part. Further, this also implies that the viscous effects in heavy ion collisions are controlled by only the system-size and not the system-shape. Had viscous effects been larger (or smaller) in events with larger ellipticity or triangularity, then these ratios would not be independent of $p_{\rm T}$.

2.2. Event-shape selected p_T spectra measurements

ALICE has also performed spectra measurements in shape-selected events. Figure 2 shows the ratio of the identified-particle p_T spectra in the top 10% of events with largest (left panel) and 10% of events with the smallest (right-panel) q_2, to the inclusive spectra for the (30-40)% centrality class. It is seen that the spectra is harder (softer) in events with larger (smaller) q_2 values. This is the first observation of correlation between radial flow and the second-order eccentricity, ϵ_2, and hence between radial and elliptic flow. Indeed, Glauber calculations show that at fixed centrality, there is a clear correlation between the initial energy density and ϵ_2 [4]. Blast-wave fits [5] to the spectra, show that the 10% of events with the largest q_2 have an $\langle\beta_T\rangle$ larger by (0.41±0.03)%, while the 10% of events with the smallest q_2 have a $\langle\beta T\rangle$ smaller by (0.22±0.03)% compared to the $\langle\beta_T\rangle$ for the inclusive case.

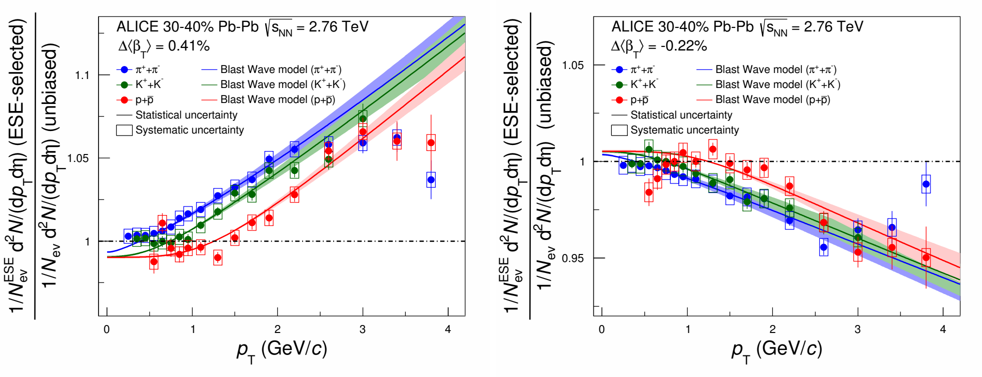

Fig. 2. The ratio of the identified particle p_T spectra in shape selected events, to the inclusive p_T spectra, for the (30–40)% centrality class. The left (right) panel corresponds to the 10% of events with the largest (smallest) q_2. The lines indicate the ratio for the blast-wave fits (see text). Figure taken from [4].

2.3. v_n–v_m correlations

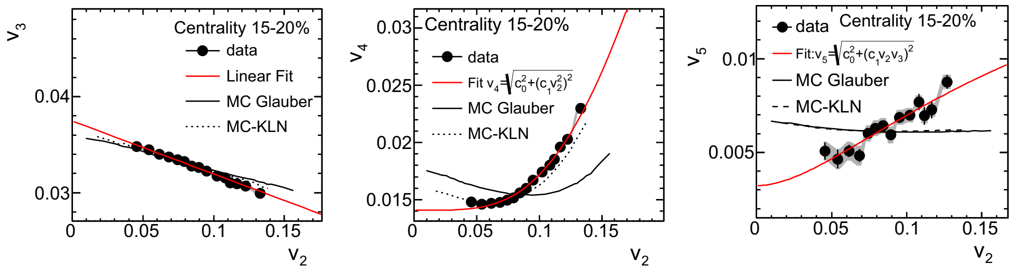

Fig. 3. Correlation between flow harmonics v_2 and v_m m=3 (left panel), 4 (middle panel) and 5 (right panel) for the (15–20)% centrality class. The correlations are measured keeping the centrality class fixed, while varying the q_2. The black lines indicate fits to MC-Glauber and MC-KLN models while the red-line indicates fits to different functional forms (see text for details). Figure taken from [3].

The event-shape selected v_n measurements also enable the study of correlations between flow harmonics different orders, *i.e.* v_n–v_m correlations. Such correlations can arise due to correlations between the ϵ_n and ϵ_m present in the initial geometry. They can also be generated dynamically due to non-linear hydrodynamic response and freeze-out effects, where a lower order ϵ_n drives a higher order v_m ($m > n$). Figure 3 shows the correlation between v_2 (x-axis) and v_n (y-axis) for n=3, 4 and 5 for the (15–20)% centrality class. Each data-point corresponds to a different q_2 class within the (15–20)% centrality interval. Also shown on the plots are the correlations between the r.m.s. ϵ_2 and ϵ_n, calculated in the Glaubler and MC-KLN models, with their mean value scaled to match the corresponding measured v_n. For the v_2–v_3 case, an roughly linear anti-correlation is observed, *i.e*. events with a larger v_2 have a smaller v_3. Dynamical effects are not expected to correlate the v_2 and v_3, thus this anti-correlation is presumably generated from initial geometry effects. Indeed, as shown on the plot, the Glauber and MC-KLN models reproduce this anti-correlation reasonably well. The anti-correlation between the ϵ_2 and ϵ_3 in the initial geometry can be understood as the following: For a given centrality, the number of participating nucleons is constrained, and arranging the nucleons to have a large ϵ_2, requires having a smaller ϵ_3 and vice versa, resulting in this anti-correlation. In the v_2–v_4 case, a strong non-linear correlation is observed. This correlation is not well described by the two initial geometry models across most centralities. From hydrodynamic simulations, it is known that the v_4 receives a non-linear contribution from ϵ_2 that goes like $(\epsilon_2)^2$. This results in the strong v_2–v_4 correlation as both harmonics are driven by ϵ_2. Starting from this picture, the v_4 can be parameterized as the quadrature sum of two components: one that is proportional to v_2^2 (as $v_2 \propto \epsilon_2$), and represents the non-linear component of v_4 driven by $(\epsilon_2)^2$, and a linear component that is independent of v_2. A fit of this form: $v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2}$ (indicated by the red line), describes the measured correlation quite well across all centralities, indicating that this v_2–v_4 correlation is indeed generated from non-linear hydrodynamic response. A strong correlation is also observed in the v_2–v_5 case as well, which is not described by the initial geometry models. As with the v_2–v_4 correlation, a two component fit of the form $v_5 = \sqrt{c_0 + (c_1 v_2 v_3)^2}$, where the $c_1 v_2 v_3$ term indicates the non-linear response: $\epsilon_2\epsilon_3 \rightarrow v_5$, describes the measured correlation quite well. Thus these v_n–v_m measurements indicate that significant fraction of the higher order harmonics, v_m for m >3 are actually driven by lower order ϵ_n ($n \leq 3$).

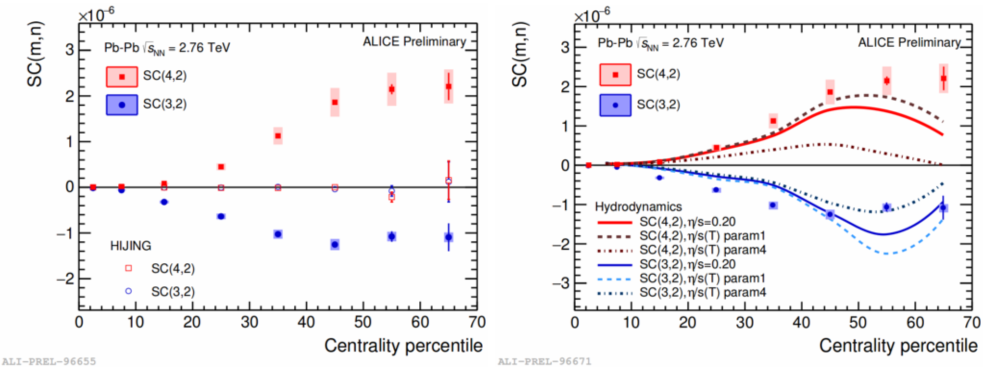

Fig. 4. The measured SC(4,2) and SC(3,2) as a function of centrality, in Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. The left panel compares the measured correlations to the corresponding quantities calculated in the HIJING event-generator. The right panel compares with the SC(m, n) calculated in hydrodynamic calculations for different parameterizations of η/s. Figure taken from [6].

The correlations between different order flow harmonics have also been studied by the ALICE collaboration. Instead of the event-shape selected measurements, ALICE uses the Symmetric 2-harmonic 4-particle cumulant defined as [6]:

$$\mathrm{SC}(m,n) = \langle\langle\cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4)\rangle\rangle - \langle\langle\cos(m\phi_1 - m\phi_2)\rangle\rangle\langle\langle\cos(n\phi_1 - n\phi_2)\rangle\rangle = \langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle,$$

where, the double averaging is over all particles within a given event and then over all events within a given centrality class. Figure 4 shows the SC(4,2) and SC(3,2) measured in Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV as a function of centrality. The left panel compares the measured values the corresponding quantities calculated in the HIJING event-generator. Since HIJING does not have any collective effects, the SC(m, n) in HIJING give a measure of how non-flow effects can affect the measurements. It is seen that the SC(m, n) are quite small and in almost all cases consistent with zero. This is not surprising, as the SC(m, n) being cumulants suppress non-flow effects. The measured SC(4,2) is positive, indicating that for a given centrality interval, events with larger v_2 on average have larger v_4. On the other hand, the measured SC(3,2) is negative indicating an anti-correlation between v_2 and v_3 at fixed centrality. This is exactly what was observed in the ATLAS event-shape selected v_2–v_n correlations. Both SC(4,2) and SC(3,2) decrease considerably in magnitude from peripheral to central events. This large decrease is artificial and does not imply that the correlations between these harmonics becomes negligible over the (0–15)% centrality interval. This decrease in the magnitude of the correlation occurs as the SC$\sim v_n^4$ (see Eq. 1) and for very central events the v_n (especially v_2) become quite small. A better correlator would perhaps be $(\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle)/\langle v_n^2\rangle\langle v_m^2\rangle$, which factorizes out the mean magnitude of the v_n^2 and v_m^2 converting it to a measurement of the relative correlation. The right panel of Fig. 4 compares the measured SC(m,n) to the corresponding quantities calculated in hydrodynamic calculations for several different parameterizations of the viscosity to entropy density ratio η/s [6]. It is seen that the SC(m,n) are quite sensitive to the η/s and thus can help in constraining it.

2.4. *Factorization breakdown in A+A and p+A collisions*

Two particle correlation (2PC) measurements in heavy ion collisions assume that the Fourier coefficients of the 2PC factorize into products of single particle flow harmonics [7]:

$$v_{n,\Delta} = v_n^a v_n^b, \tag{1}$$

where, $v_{n,\Delta}$ indicates the n^{th} order Fourier coefficient of the 2PC, and v_n^a and v_n^b indicate the flow harmonics for the particles labelled a and b, that are used in the 2PC. However, if the event-plane angles, Ψ_n, have explicit dependence on p_{T} and η, this factorization breaks [7]. Since the eccentricities of the forward and backward-going participant nucleons are not identical, one expects some systematic rotation of the Ψ_n angles as a function of η. This dependence of the Ψ_n on η, and the consequent breakdown of the 2PC factorization, has been measured by the CMS collaboration. In the presence of a η dependent Ψ_n, the n^{th} order Fourier coefficients of the 2PC between particles at pseudorapidity η^a and η^b, is given by [7]:

$$v_{n,\Delta}(\eta^a,\eta^b) = \langle v_n(\eta^a)v_n(\eta^b)\cos(n\Psi_n(\eta^a) - n\Psi_n(\eta^b))\rangle, \tag{2}$$

where the averaging is over all events. The measurement of the Ψ_n rotation was done by correlating particles at pseudorapidity $+\eta^a$ and $-\eta^a$, with reference particles at η^b. The ratio of the $v_{n,\Delta}$ from these two 2PCs becomes:

$$\begin{aligned} r_n(\eta^a,\eta^b) \equiv \frac{v_{n,\Delta}(\eta^a,\eta^b)}{v_{n,\Delta}(-\eta^a,\eta^b)} &= \frac{\langle v_n(\eta^a)v_n(\eta^b)\cos(n\Psi_n(\eta^a) - n\Psi_n(\eta^b))\rangle}{\langle v_n(-\eta^a)v_n(\eta^b)\cos(n\Psi_n(-\eta^a) - n\Psi_n(\eta^b))\rangle} \\ &\approx \langle\cos(n\Psi_n(\eta^a) - n\Psi_n(-\eta^a))\rangle \approx 1 - 2\eta^a F_n^\eta. \end{aligned} \tag{3}$$

The approximations in the last two lines of Eq. 3 assume that the fluctuations in the magnitudes of the v_n at different η are independent of the Ψ_n rotations, and that the rotations in the Ψ_n are small. The $r_n(\eta^a,\eta^b)$ (and the F_η^n) are thus a measure of the Ψ_n angle rotation, and of η dependent factorization breakdown in 2PCs. Detailed measurement of the $r_n(\eta^a,\eta^b)$ in Pb+Pb and p+Pb have been done by CMS [7]. The measurements show that except in very central Pb+Pb collisions, the $r_n(\eta^a,\eta^b)$ are linear functions of η^a and thus, the approximations Eq. 3 are justified. Figure 5 shows the parameter F_η^n obtained by fitting the measured $r_n(\eta^a,\eta^b)$ with the functional form $1-2\eta^a F_n^\eta$, as a function of event multiplicity. Results are shown for n=2–4 in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=2.76 TeV and for n=2 in p+Pb Collisions at $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV The F_η^2 in Pb+Pb collisions reaches a minimum in mid-central events, and increases for more central and more peripheral events. The factorization breakdown is much larger for higher order harmonics n=3 and 4. The F_η^2 in p+Pb collisions is significantly larger than in that in Pb+Pb collisions with the same multiplicity indicating that the rotation or fluctuation of the Ψ_2 angle is much larger in p+Pb collisions. CMS has also published similar measurements of the factorization breakdown as a function of p_{T} in Pb+Pb and in p+Pb collisions [7].

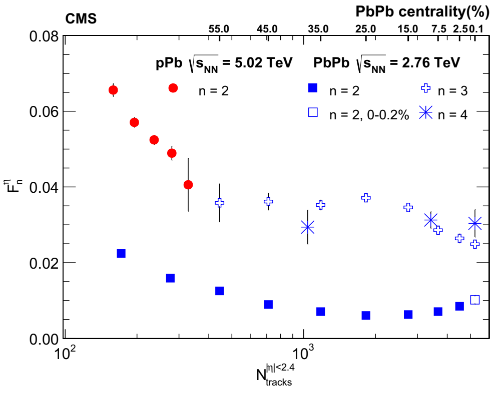

Fig. 5. The F_η^n parameter for n=2–4, in Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV, and for n=2 in p+Pb Collisions at $\sqrt{s_{NN}}$=5.02 TeV. The values are plotted as a function of event multiplicity, defined as the number of reconstructed charged particle tracks with p_T >0.4 GeV and $|\eta|$ <2.4. Figure taken from [7].

2.5. *Principal component analysis of v_n*

One of the reasons for p_T dependent factorization breakdown in 2PCs is that there are multiple sources driving the same order harmonic flow. These sources can be, for example different radial modes in the eccentricities of the initial geometry [8]. A principal component analysis (PCA) was proposed in [9], which, starting from the 2PC Fourier coefficients, can obtain the single-particle anisotropies corresponding to different sources. The contribution of the individual sources to the v_n are called "*modes*", with the largest contributor called the leading and the second largest contributor called the sub-leading mode.

Figure 6 shows CMS measurements of the leading and sub-leading modes for the flow harmonics v_2 and v_3 in p+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. Also shown for comparison is the traditional 2PC measurement of the v_n. For both v_2 and v_3, it is seen that the leading mode is almost identical to the 2PC measurement. For v_2, the sub-leading mode is consistent with zero at low p_T but increases to ∼ 5% at p_T ∼3 GeV, indicating the onset of factorization breakdown at this p_T. For v_3 the sub-leading mode at all p_T is small compared to the leading mode, indication that factorization works better for v_3, as previously observed in [7].

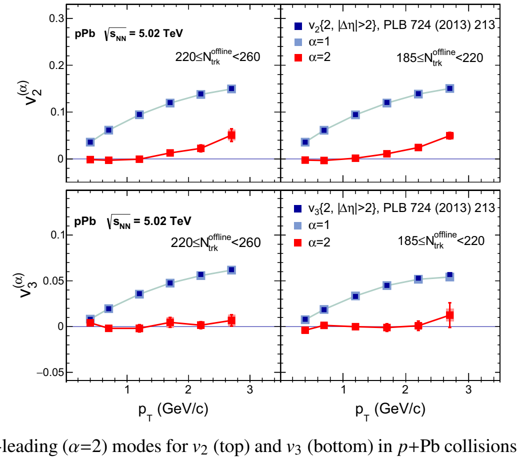

Fig. 6. The leading (α=1) and sub-leading (α=2) modes for v_2 (top) and v_3 (bottom) in p+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. Each panel presents results for a particular centrality bin. Figure taken from [10].

2.6. Flow in small systems

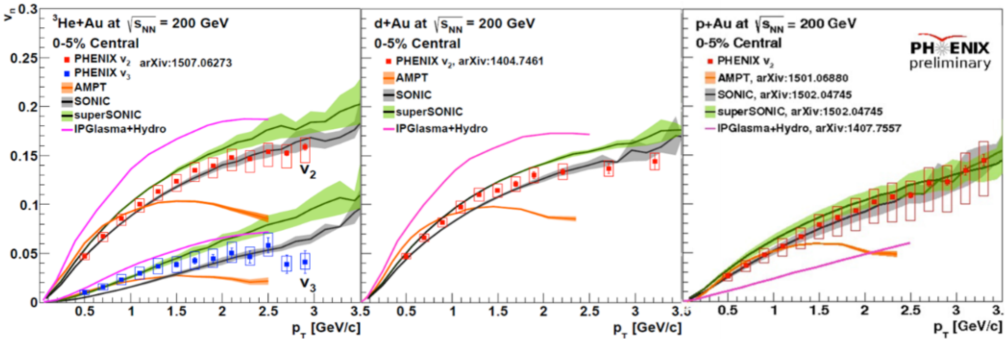

Fig. 7. The $v_n(p_T)$ measured in ^{3}He + Au (left panel), d+Au (middle panel) and p+Au (right panel) collisions at $\sqrt{s_{NN}}$=200 GeV. The measurements are for the (0–5)% centrality class in all three cases.

Much progress has been made in the measurement of correlations in small systems with new v_n measurements in ^{3}He + Au and p+Au collisions at $\sqrt{s_{NN}}$=200 GeV from the PHENIX collaboration. Fig 7 shows these results along with previous d+Au measurements for the (0–5)% centrality class in each case. It is interesting to note that the v_2 values in ^{3}He + Au and d+Au collisions for this centrality class, are quite comparable. All measurements are compared with four theory calculations from transport and hydro models. Both SONIC and superSONIC calculations which employ a combination of hydro and hadronic cascade reproduce the measured v_n values reasonably well. Additionally, PHENIX measurements of identified charged hadron v_2 in ^{3}He + Au collisions [11], and new CMS measurements of K_S^0 and Λ v_2 in p+Pb collisions [12] exhibit quark number scaling as seen in A+A collisions. These measurements together are strongly indicative of collective effects in these smaller systems.

Significant advancements in the analysis of long-range correlations in pp collisions were made by the ATLAS and CMS collaborations [13, 14]. Previous correlation measurements in pp were severely limited, due to the presence of the large away-side jet, which made it impossible to study the full $\Delta\phi$ dependence of the long-range correlation. ATLAS and CMS have now devised subtraction procedures that account and remove the contribution of "*jet*" correlations to the 2PCs, revealing the genuine long-range correlations [13, 14]. ATLAS has shown that the second Fourier coefficient of the genuine long-range correlations, factorizes into products of single particle anisotropies (v_2) like in A+A collisions. Figure 8 shows the measured single-particle v_2 values measured by ATLAS in pp collisions at $\sqrt{s}$=2.76 TeV (left) and 13 TeV (right) as a function of the event multiplicity. It is seen that not only is the v_2 independent of the event multiplicity, it is also quite consistent between the two collision energies. It would be interesting to see if theory calculations from initial-geometry and hydro models can or cannot reproduce the measured energy and multiplicity independence.

3. Summary

A large set on interesting new flow measurements were presented at Quark Matter 2015. In the traditional A+A systems, these included event-shape selected v_n measurements, which give clear evidence of correlations between radial and elliptic flow. These measurements also establish that viscous effects in heavy ion collisions depend on the system size and not on the system shape. Measurements of correlations between different order flow harmonics were presented. Such correlations clearly establish the presence non-linear hydrodynamic response in heavy ion collisions, where higher order flow harmonics are driven by lower order eccentricities in the initial collision geometry. It was shown that these correlations are very sensitive to the η/s, but not the initial geometry, and perhaps in the future can help in strongly constraining the η/s and its temperature dependence. Measurements of multi-particle correlations for identified and inclusive

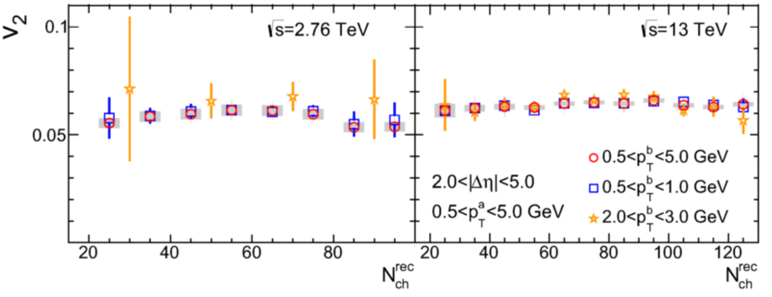

Fig. 8. The single-particle v_2 values measured in pp collisions at $\sqrt{s}$=2.76 TeV (left panel) and 13 TeV (right panel) as a function of the event multiplicity. The event multiplicity is defined as the number of reconstructed charged particle tracks with p_T >0.4 GeV and $|\eta|$ <2.5. Figure taken from [13].

charged hadrons, in smaller systems such as p+A, d+A and ^{3}He+A were presented, that are supportive of collective effects effects in such systems. The first studies of long-range correlations in pp collisions with the "*jet*" component removed were presented. It was shown that the genuine long-range correlation is well described by single-particle elliptic anisotropies (*i.e* v_2), indicating the possibility of collective phenomena even in pp collisions. Further, it was shown that the long-range correlation in pp collisions is present at all multiplicities, and not just in high multiplicity events.

Acknowledgments

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